

into or out of the fingertip at array 15 as different virtual articles or environments are displayed.

In tactile graphic design there is a tradeoff between complexity of implementation and realism. Improved realism (making the experience using the display more like a real-life experience) may be desirable and (as heretofore suggested) implementable, but it is not necessary to have perfect realism for a display to be quite usable for most applications. Safety of such systems is also an issue. Most users will not want to actually be injured if the display apparatus is attempting to reproduce a pinprick. Designers may impose limits on the amount of force that a tactile graphic display stimulus point 17 may apply, on the “sharpness” of the application of force (the small-area differential in force applied to the skin), and possibly the magnitude, frequency and duration of vibrations applied to the skin. One factor that may influence designers is that reducing the magnitude of the forces applied to the skin by the display reduces the impact of the safety issues while also reducing cost of construction and operation.

When a fingertip display array 15 is integrated into a data glove 23 with force feedback, the forces applied to the skin by array 15 are superimposed over the forces applied by the haptic system. In a real world situation, the detailed textural information picked up by the finger may be thought of as a differential pressure signal that is proportional to the total pressure being applied to the skin. It will therefore increase the realism of the combined tactile/haptic system if the differential pressure applied by the tactile display array 15 is made to increase when the pressure applied by the haptic system increases. In the real world this would be a linear relationship. In a display system of this invention, the maximum pressure that can be applied by the tactile display may be considerably less than the maximum pressure that can be applied by the haptic system, so some other mapping function of haptic system force to tactile system pressure may be needed. For example, the relation may be linear at low force levels, then taper off toward the point at which the tactile display is exerting maximum differential pressure. Another approach is to keep the relationship linear until the tactile display reaches maximum output, then to keep the differential constant from that point on. Either approach can provide sufficient realism to make the tactile/haptic system useful. It should be noted that the pressure-based tactile display apparatus of this invention can achieve adjustment of the differential pressure either by modulation of the fluid flow to the individual stimulus points 17, by varying the pressure of the fluid to modulator 29, or a combination of both. The ability to vary the pressure of the fluid to the modulator may be particularly useful because it is adjusted for the entire localized body area in contact with array 15 in much the same way that the force to the body area by the haptic system is applied, and because it will not interfere with the modulator’s ability to provide a wide range of forces to individual stimulus points 17.

Another design factor for data glove 23 applications is the thickness of the display structure. If the user initiates a motion that would bring two fingertips together (for example), then the thickness of the display limits the proximity of the two fingertips. Thus the display (i.e., matrix/stimulus points combination) should be as thin as possible and likely will require placement of modulator 29 remote from display array 15. Use of a multiplexing mechanism at the output from modulator 29 will permit a reduction in the number of fluid channels 27 from a remotely positioned modulator to array 15. Positional details of relative spacing between two opposed fingertips might be more important

than absolute spacing provided that absolute spacing is not inhibited to the degree that it would interfere with positions and angles of the fingers. When creating a mental model of the dimensions of an object being grasped, the user may learn to ignore the thickness of the display apparatus at the body locale and concentrate on the differential signal provided by the display apparatus.

It is important to note that the output of the pressure-based tactile display apparatus of this invention is effectively a differential signal, whether or not it is combined with a haptic system. If the same force is applied to all the stimulus points 17, the perceived sensation will be much the same as when no force is applied to any of the stimulus points. This is a good match for detailed sense of touch in humans, which depends on differences in pressure and changes over time to collect tactile information. A display driving algorithm should, therefore, concentrate on such differentials applied at array 15 thereby minimizing power consumption while producing a useful tactile signal and providing a differential signal margin adequate to allow reasonable changes in what is being displayed over a short time interval. The driving algorithm must also take into account the maximum frequency and other capabilities of the apparatus, the degree of realism needed, and the texture and rate of change in motion of the virtual surface being displayed. The modulation frequency needed is increased by higher density of stimulus points 17, by increases in the number of intensity levels needed, by increases in the velocity of the virtual surface being displayed, and by the effort to avoid the unintended perception of vibration.

Methods that may be used in the display driving algorithm include implementation of multiple pressure levels by rapid sequencing of pseudorandom patterns so that each stimulus point is driven the correct fraction of the time, while any unintended vibration or motion felt by the user is minimized. For representation of very rapid lateral motion, the performance bandwidth of the tactile display may not be adequate to recreate the motion of a detailed surface with complete accuracy. However, the human sense of touch is unable to maintain full detail spatial resolution during rapid motion. The driving algorithm can take advantage of this limitation in human perception and produce a stimulus that, while lacking in the full detail and motion, conveys to the user enough information to produce a realistic sensation. Specific techniques may include driving only a subset of the total collection of tactile stimulus points 17 during rapid motion and skipping steps in the lateral propagation of patterns.

The refreshable scanning tactile graphic display apparatus and methods for localized sensory stimulation of this invention can be used in many applications. The display apparatus provides much of the functionality of a large-area refreshable tactile display in a smaller package and with a greatly reduced number of stimulus points. By integrating one or more fingertip arrays 15 into data glove 23, a detailed sense of touch can be added to the virtual environment, and integrated with existing haptic technology. The tactile display apparatus can be included in an augmented reality system that combines elements of the real world and virtual reality (for example, a robot manipulator device that is operated by remote control (teleoperation) can be equipped with pressure sensor arrays to give it a “sense of touch”, signals from the arrays being relayed to a human operator using the apparatus of this invention, who then has tactile input, not merely sight, to guide operation of the manipulator). Fingertip tactile display apparatus of this invention can be put into the fingers of a protective suit, with sensors or mechanical linkages on the outside of the fingers of the